(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 954 144 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
03.11.1999 Bulletin 1999/44

(51) Int Cl.6: H04L 25/02

(21) Application number: 99303283.8

(22) Date of filing: 27.04.1999

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: 30.04.1998 EP 98303417

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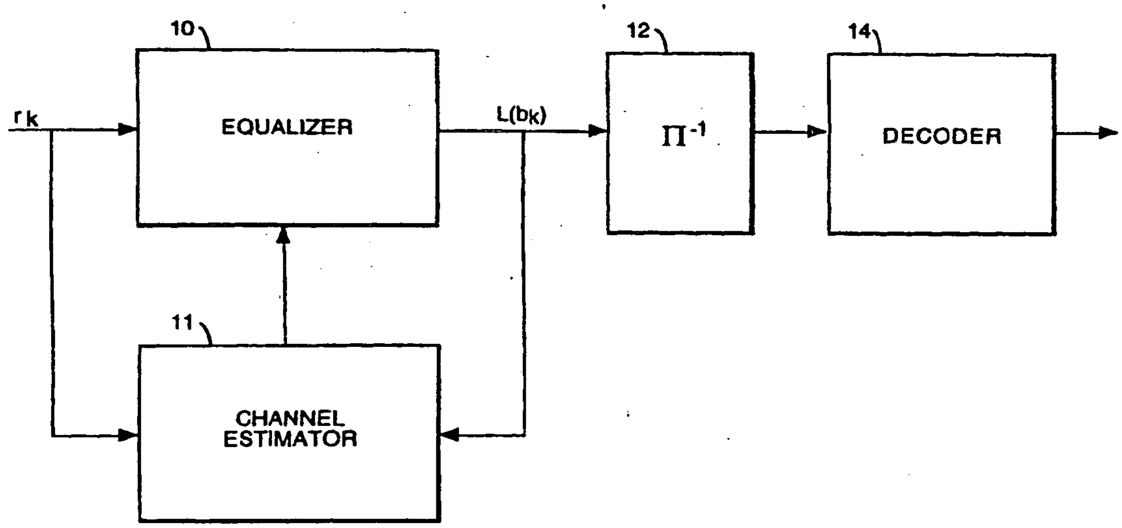
(54) Channel estimation using soft-decision feedback

(57) A method of estimating channel impulse response in a signal transmitted over a channel in a communication system is described. The channel estimator obtains *a priori* knowledge about the transmitted signal and then use the transmitted signal and the a priori knowledge to choose an estimate of channel impulse response which minimises the expected distance between the transmitted signal and a reconstructed signal. The expected distance that is minimised is a cost function, represented by $E\{\|r - Bh\|^2 | r\}$. By using soft decision feedback, the invention minimises erroneous decision feedback which can cause error propagation. The decision are usually in the form of log likelihood ratios (LLR).

Fig.1.



EP 0 954 144 A1

Printed by Jouve, 75001 PARIS (FR)

Description

[0001] This invention relates to channel estimation methods and apparatus in mobile radio communications which adaptively compensate for channel distortion on a block-by-block basis.

[0002] In digital mobile radio communications, transmission channels suffer from severe distortion due to frequency selective fading. In addition, channel characteristics are normally time-varying due to the relative motion of fixed and mobile stations. Inter-symbol interference (ISI) is one of the primary impediments to reliable estimates of the transmitted data. In order to allow for reliable transmission, the receiver must be able to estimate and compensate for channel distortion on a block-by-block basis. Equalisation schemes usually employed in modem mobile communications rely on an estimate of the channel, generated from a known training sequence, inserted into the transmitted signal block. Equalisation may be improved by means of decision feedback, as described in K.H. Chang and C.N. Georghiades in "Iterative Join Sequence and Channel Estimation for Fast Time-Varying Inter-symbol Interference", Proc. Intern. Conf. Commun. Pp.357-361, June 1995 [Reference 1].

[0003] There is thus a requirement for an equalizer with improved performance and which reduces the effects of error propagation.

[0004] According to a first aspect of the invention there is provided a method of estimating channel impulse response in a signal transmitted over a channel in a communication system characterised by obtaining *a priori* knowledge about the transmitted signal and using the transmitted signal and the said a priori knowledge to choose an estimate of channel impulse response which minimises the expected distance between the transmitted signal and a reconstructed signal.

[0005] In hard decision feedback the decisions are assumed to be correct and are used in addition to a training sequence but erroneous decisions cause error propagations. With soft decision feedback, however, the decision are usually in the form of log likelihood ratios (LLR).

[0006] A detailed description of the invention, using by way of illustration a practical digital radio receiver, is described below with reference to the following figures in which:

[0007] Figure 1 shows in outline an equalizer for a digital radio receiver.

[0008] The discrete-time received signal r_k of figure 1 can be written as

$$r_k = \sum_{l=0}^{L-1} b_{k-l}\, h_l + n_k \qquad (1)$$

where $b_k \in \{-1,1\}$ are the transmitted data symbols or known training sequence symbols, the L complex tap-gains h_l represent the samples of the equivalent channel impulse response, and n_k indicates additive white Gaussian noise with zero mean and variance σ^2. Channel equalisation is commonly performed by maximum likelihood (ML) or maximum *a posteriori* probability (MAP) data estimation. In both cases, the receiver must first estimate, in the channel estimator 11, the channel impulse response h_l, which is required in the data estimation process, carried out in the equalizer 10. The data output L (b_k) is then deinterleaved, as indicated by Π^{-1} (12) in figure 1 and decoded (1_4) The initial channel estimation is usually obtained by means of correlative channel sounding. In this case, the samples of the CIR estimate are obtained by correlating the received signal r_k with N=16 bits b_k out of the 26 bits training sequence:

$$\hat{h}_l = \frac{1}{N} \sum_{i=0}^{N-1} b_i\, r_{l+i} + n_k\,, \quad l=0, \ldots, L-1 \qquad (2)$$

[0009] Due to the good autocorrelation properties of the GSM training sequence, the correlative channel sounding technique corresponds to ML channel estimation.

[0010] Once the channel estimate is available, the estimation of the data symbol sequence is performed. If the channel cannot be considered approximately constant within one burst, the initial channel estimate can be updated during the burst by using the decisions at the equaliser output. The equaliser soft-output sequence is finally de-interleaved and decoded.

[0011] Maximum likelihood sequence estimation implemented by the Viterbi algorithm (VA) is the optimum sequence detector, such as described in G.D. Forney, Jnr., "Maximum Likelihood Sequence Estimation of Digital Sequences in the presence of Intersymbol Interference", IEEE Trans. Inform. Theory, vol. IT-18, pp 363-378, May 1972 [reference 2]. It is widely used in digital mobile receivers for processing both the ISI trellis (equalisation) and the channel code trellis (channel decoding). However, the channel decoder performance is improved by an equaliser which provides soft

values at the decoder input. Furthermore, in some advanced schemes implementing iterative equalisation and decoding and/or source controlled channel decoding, such as described in J. Hagenauer, "Source Controlled Channel Decoding", IEEE Trans. On Commun, Vol 43, no 9, PP 2449-2457 Sept 1995 [reference 3], the channel decoder must be able to provide soft-outputs for the coded bits and for the information bits.

[0012] In terms of bit-error probability, the optimum algorithm for soft-in/soft-out equalisation and decoding is the symbol-by-symbol MAP algorithm. In fact, being an a posteriori probability (APP) calculator, it intrinsically provides soft output values.

[0013] In a hard decision (HD) feedback scheme all decisions are assumed to be correct and may be used as an additional training sequence. By using vector notation the received signal may be described as

$$\underbrace{\begin{pmatrix} r_{L-1} \\ \vdots \\ r_{N-1} \end{pmatrix}}_{\mathbf{r}} = \underbrace{\begin{pmatrix} b_{L-1} & b_{L-2} & \cdots & b_0 \\ b_L & b_{L-1} & \cdots & b_1 \\ \vdots & \vdots & \ddots & \vdots \\ b_{N-1} & b_{N-2} & \cdots & b_{N-L} \end{pmatrix}}_{\mathbf{B}} \underbrace{\begin{pmatrix} h_0 \\ \vdots \\ h_{L-1} \end{pmatrix}}_{\mathbf{h}} + \underbrace{\begin{pmatrix} n_{L-1} \\ \vdots \\ n_{N-1} \end{pmatrix}}_{\mathbf{n}}$$

where **r** is the received signal vector, **B** is the matrix with the transmitted bits, **h** denotes the channel vector, and **n** the channel noise. Since we assume binary signalling, the transmitted bits b_k take on the values ±1. The matrix product **Bh** corresponds to the convolution between b_k and h_k (see equation (1)). Note that the above notation assumes the channel to be constant over the block of transmitted data.

[0014] The least square (LS) estimate of the channel is

$$\hat{h}^{HDLS} = (B^H B)^{-1} B^H r$$

where H denotes Hermitian transpose and the inverse is assumed to exist.

[0015] With soft decision (SD) feedback, the soft output of the equaliser is fed back to the channel estimator. The soft output is usually in the form of a log-likelihood ratio (LLR)

$$L(b_k|r) = \log \frac{\Pr(b_k = +1|r)}{\Pr(b_k = -1|r)} \tag{3}$$

which may equivalently be written as a probability

$$\Pr(b_k|r) = \frac{e^{\frac{1}{2}L(b_k|r)}}{e^{\frac{1}{2}L(b_k|r)} + e^{\frac{1}{2}L(b_k|r)}}$$

[0016] This *a posteriori* probability from the equaliser can be used as *a priori* knowledge for the channel estimator. A possible, but by no means unique, cost function to minimise would be

$$E\left\{\|\mathbf{r} - \mathbf{Bh}\|^2 \middle| \mathbf{r}\right\} = E\left\{\sum_{k=L-1}^{N-1} |r_k - h_k * b_k|^2 \middle| \mathbf{r}\right\} \tag{4}$$

where the expectation is taken over the bits b_k conditioned on the received sequence **r**. This cost function represents the average (or expected) distance between the received signal and a reconstructed signal. To minimise the cost function (4) it is differentiated with respect to the channel

$$\frac{\delta}{\delta\hat{\mathbf{h}}}E\left\{\|\mathbf{r}-\mathbf{Bh}\|^2\,\middle|\,\mathbf{r}\right\}=E\left\{\frac{\delta}{\delta\hat{\mathbf{h}}}(\mathbf{r}-\mathbf{Bh})^H(\mathbf{r}-\mathbf{Bh})\,\middle|\,\mathbf{r}\right\}=0\Rightarrow$$
$$E\left\{-\mathbf{B}^H\mathbf{r}+\mathbf{B}^H\mathbf{Bh}\,\middle|\,\mathbf{r}\right\}=0\Rightarrow\hat{\mathbf{h}}=\left(\overline{\mathbf{B}^H\mathbf{B}}\right)^{-1}\overline{\mathbf{B}}^H\mathbf{r}$$

where $\overline{\mathbf{B}^H\mathbf{B}} = E\{\mathbf{B}^H\mathbf{B}\}$ and $\overline{\mathbf{B}} = E\{\mathbf{B}\}$. For soft decision

$$E\left\{b_k b_l\middle|\mathbf{r}\right\}=\begin{cases}\bar{b}_k\bar{b}_l & k\neq l\\ 1 & k=l\end{cases}$$

where $\bar{b}_k = E\{b_k r\} = 2\Pr(b_k +1|\mathbf{r})-1$. Note that this value is always in the range [-1,+1]. The expectation of $\mathbf{B}^H\mathbf{B}$(see page 3) now becomes:

$$\overline{\mathbf{B}^H\mathbf{B}}=\begin{bmatrix} N-L+1 & \bar{b}_{L-1}\bar{b}_L+\ldots+\bar{b}_{N-2}\bar{b}_{N-1} & \cdots & \bar{b}_0\bar{b}_L+\ldots+\bar{b}_{N-L-2}\bar{b}_{N-1}\\ \bar{b}_{L-1}\bar{b}_L+\ldots+\bar{b}_{N-2}\bar{b}_{N-1} & N-L+1 & \cdots & \bar{b}_0\bar{b}_{L-1}+\ldots+\bar{b}_{N-L-2}\bar{b}_{N-2}\\ \vdots & \vdots & \ddots & \vdots\\ \bar{b}_0\bar{b}_L+\ldots+\bar{b}_{N-L-1}\bar{b}_{N-1} & \bar{b}_0\bar{b}_{L-1}+\ldots+\bar{b}_{N-L-1}\bar{b}_{N-2} & \cdots & N-L+1\end{bmatrix}$$

[0017] The off-diagonals of $\overline{\mathbf{B}^H\mathbf{B}}$ are small compared to the main diagonal terms. By ignoring them we have the simplification

$$\overline{\mathbf{B}^H\mathbf{B}} \approx (N-L+1)\mathbf{I} \tag{5}$$

and the simplified estimator (channel sounding) becomes

$$\begin{aligned}\hat{\mathbf{h}}^{HDCS}&=\frac{1}{N-L+1}\overline{\mathbf{B}}^H\mathbf{r}\\ \hat{h}_m^{HDCS}&=\frac{1}{N-L+1}\sum_{k=L-1}^{N-1}r_k\bar{b}_{k-m}\\ \bar{b}_{k-m}&=E\{b_k\}=2\Pr\left(b_k=+1\middle|\mathbf{r}\right)-1=\tanh\left(\frac{L\left(b_k\middle|\mathbf{r}\right)}{2}\right)\end{aligned} \tag{6}$$

[0018] Although the equaliser provides the log-likelihood ratios

$$L(b_k|\mathbf{r}),$$

these can easily be transformed by a lookup table to produce $\bar{b}_k$.

[0019] The above analysis also applies to the case where the channel estimator is obtained by feeding back the L-values of the coded bits provided by the channel decoder.

[0020] At low SNR the invention performs significantly better than hard decisions. From (6), where bits b_k are uncertain (say, $\Pr(b_k = +1/r) = 0.6$) will produce a soft value (in this case $\bar{b}_k = 0.2$), whereas bits with a high reliability will give soft values close to ±1. This means that when a decision error occurs at the equalizer output, the probabilities Pr

(b_k = +1lr) often indicates a weak reliability which the channel estimator can use to reduce the effects of error propagation.

[0021] At higher SNR, simulation show that least squares estimators perform significantly better than channel sounding, since least squares estimators can use the soft information to optimally weigh the feedback bits. At higher SNR, approximations (2) and (5) become significant, whereas with a low SNR this approximation error is concealed by the channel noise.

[0022] Simulations have also shown that the invention provides an improvement of about 0.8 dB with channel sounding and about 0.9 dB with a least squares estimation. Another advantage of the invention is that it does not require any matrix inversion.

Claims

1. A method of estimating channel impulse response in a signal transmitted over a channel in a communication system characterised by

    obtaining *a priori* knowledge about the transmitted signal
    using the transmitted signal and the said a priori knowledge to choose an estimate of channel impulse response which minimises the expected distance between the transmitted signal and a reconstructed signal.

2. A method as claimed in claim 1 characterised in that the expected distance that is minimised is a cost function.

3. A method as claimed in claim 2 characterised in that the cost function that is minimised is represented by

$$E\{\|r-Bh\|^2 \mid r\}.$$

4. A method according to any preceding claim characterised in that the a priori knowledge is obtained from data estimation performed on the transmitted signal.

5. A method according to any preceding claim characterised in that the a priori knowledge is obtained from a channel decoder.

6. A method as claimed in any preceding claim characterised in that the choosing the estimate from channel sounding.

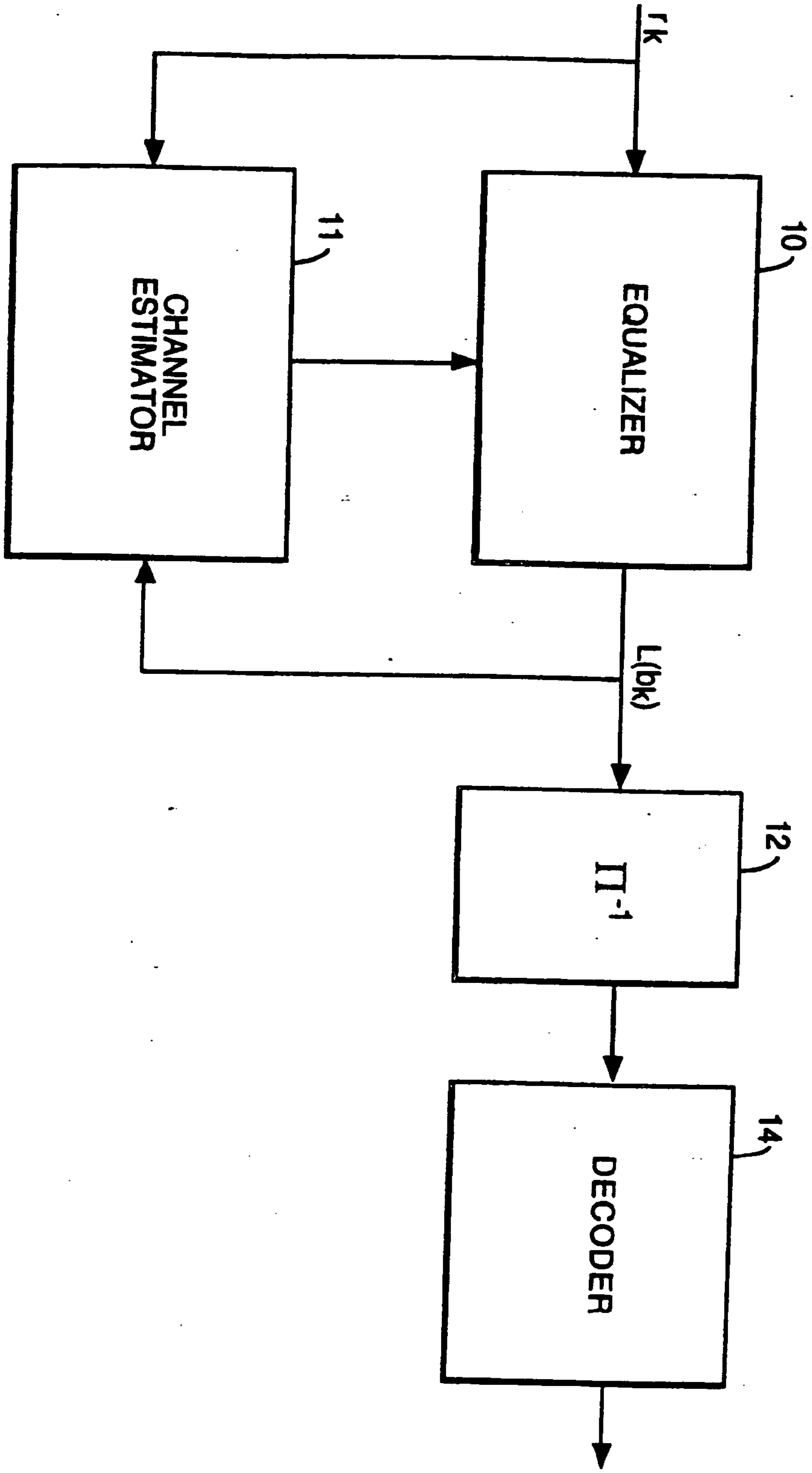


Fig.1.

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EUROPEAN SEARCH REPORT

Application Number
EP 99 30 3283

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	16 July 1999	Koukourlis, S

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